



Opinion Article

Directions in internal combustion engine research

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1. Introduction

Why do we still need research on Internal Combustion (IC) engines? Society continues to rely heavily on IC engines for transportation, commerce, and power generation. That is why engine research has enjoyed a more than century-long history, and engine research is still vibrant today. Reciprocating Internal Combustion (IC) engines range in size from model airplane engines that fit in the hand, to gigantic marine engines as tall as a four story building. IC engines power all manner of utility devices (e.g., pumps, mowers, chain-saws, portable generators, etc.), earth-moving equipment, tractors, propeller aircraft, ocean liners and ships, personal watercraft and motorcycles, plus the 750 million passenger cars on the world's roads. And, if you just look at the U.S., there are 250 million vehicles – that's roughly one per person. Sixty million cars will be made in the world in 2012, which is a 50% increase over a decade ago. Part of this increase is due to the fact that China became the world's largest car market in 2011 and is now producing a quarter of the world's cars. A third of all cars produced are made in the European Union, and half are powered by diesel engines, partly due to their higher fuel efficiency. So, engine research encompasses both gasoline and diesel engines, and even small improvements in their efficiency have a major impact on economy and pollution.

The huge number of vehicles and engines on the planet burns a vast quantity of fuel. Indeed, 70% of the 86 million barrels of crude oil that we consume every day is used in IC engines. And, in the U.S., 10 million barrels are used per day in cars and light-duty trucks, plus 4 million in heavy-duty vehicles, which works out to about 2.5 gallons per person every day. Since there are insufficient fuel reserves to meet this consumption, 62% is imported and, at current prices (e.g., \$80 a barrel), the U.S. spends about 1 billion dollars a day on imported oil. This cost is certain to increase as more-and-more economic development drives increased demand for automotive fuels world-wide.

Associated with this massive oil use is the accompanying emission of pollutants, including nitric oxides (NO_x) and particulates (soot), as well as the production of CO₂. Pollutant emissions have serious environmental and health implications, and thus most governments have imposed stringent vehicle emissions regulations that are continually being tightened further. In addition, the

world's annual production of 37 billion tons of CO₂ contributes to Green House Gases (GHG), which some fear could lead to climate change with unpredictable consequences. Drastic reductions in fuel usage would be required to make appreciable changes in GHG trends. For example, the International Energy Agency roadmap is to reduce fuel use per kilometer by 30–50% in new road vehicles worldwide by 2030, and from all vehicles by 2050. The goal is to limit the global average temperature rise which some climatologists project for 2050 (the 2DS scenario) [1]. Government mandates requiring such reductions impose a tall order on the already high-tech and high-cost automotive industry. And, although 2050 seems a long time in the future, the time required to bring new engines to production, together with the years needed for new technology to permeate the overall vehicle fleet, means that major effort (and investment) is needed in IC engine research over the next decades.

So, why do we still use gasoline and diesel fuels? They are a compact and portable form of energy, providing over 40 MJ per kg of fuel. Considering that the kinetic energy of a thousand kg automobile traveling at 60 mph is about the amount of energy in only a 1/3 of an ounce, or a teaspoon of gasoline or diesel fuel, the appeal is obvious. The high energy density of liquid petroleum fuel comes from breaking and rearranging its molecular bonds, producing CO₂ and H₂O from large molecular weight hydrocarbons. However, we do not actually harness all of this energy. Getting the fuel from the oil well to the gas station requires about a 20% equivalent amount of energy to that contained in the fuel. Once the fuel enters the vehicle's gas tank the typical Spark-Ignition (SI) automotive engine delivers about 18% of this energy to its drive train. Engine and exhaust losses account for about 62% of the loss, and about 20% is consumed in running accessories and stand-by-idle. More losses occur in the driveline, so that only about 12% of the fuel tank energy actually makes it to the wheels.

In view of the well-documented inefficiencies of the IC engine, there is perennial discussion about displacing it with some more energy-efficient power-plant. However, no such power-plant has emerged in spite of billions of dollars and decades of research since the invention of the automobile more than a century ago. New ideas are regularly proposed, but cost, complexity and overlooked real-world design shortcomings usually restrict their implementation. Examples that have not seen much success include Stirling, rotary, solar and hydrogen power-plants, and recently fuel cell powered vehicles. Electric hybrid or battery powered vehicles have benefits in some light-duty applications, but their advantages

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depend heavily on the duty cycle, favoring city more than long distance driving. Also, it is important to note that the thermal efficiency of electricity generation at power stations (to charge plug-in hybrid and battery vehicles) is generally less than 50%. This limits the overall energy efficiency severely from the very outset. In addition, further losses need to be considered, such as those from mining and transporting the fuel to the power station (e.g., coal/natural gas), distributing the power to the end user, and energy storage losses – plus those accessory and driveline losses on the vehicle itself.

With this in mind, the relative low cost, high durability and convenience of the IC engine, coupled with its ability to use high-energy-density liquid fuels, makes it difficult to make the case to displace it. Indeed, a recent NRC report [2] concluded:

There seems to be little doubt that, regardless of the success of any pathways discussed, the internal combustion engine (ICE) will be the dominant prime mover for light-duty vehicles for many years, probably decades. Thus, it is clearly important to perform R&D to provide a better understanding of the fundamental processes affecting engine efficiency and the production of undesirable emissions.

In addition, there is no obvious alternative to the IC engine for the medium- and heavy-duty commercial vehicle markets, and these applications account for a quarter of all fuel used (mostly diesel). However, it is also clear that the sustainability of the world's appetite for fossil oil is not justifiable in the longer term, and this drives the need for more research. Absent the arrival of some magic bullet power-plant, the world will continue to rely almost entirely on the IC engine which, by the way, can be transformed to run on non-fossil fuel sources, such as renewable bio-fuels.

2. Opportunities and challenges in engine research

As discussed above, there is great incentive to reduce petroleum dependence and to make the best use of the world's limited fossil fuel resources by improving IC engine efficiency through research. It is also important to seek and explore new engine concepts that use alternative fuels, such as renewable bio-, or natural gas- and coal-derived fuels, so as to reduce the monopoly of fossil oil. Of course, these engine performance enhancements must be made while meeting stringent pollutant emissions mandates. The engine must perform reliably over wide ranges of engine speed and load, and must start and operate under all climates and terrestrial elevations.

After over a century of intensive development, it is remarkable that significant improvements to IC engine efficiency are still being made. This reflects the richness of the combustion process, which still presents opportunities for new discoveries. Engine combustion can be characterized as a low Mach number, compressible, multi-phase, high-Reynolds number turbulent flow with chemical reactions and heat transfer, confined in a time-varying geometry. The combustion process spans multiple regimes that include turbulent flame propagation, mixing-controlled burning, and chemical-kinetics-controlled processes, plus their combinations. Describing these complex interacting processes certainly classifies understanding engine physics as a “grand challenge” problem. Indeed, Prof. Phillip S. Myers, who founded UW-Madison's Engine Research Center in 1946, often observed that the IC engine is also the perfect teaching tool, since it relies on all areas of Mechanical Engineering, with the possible exception of nuclear reaction!

Engine research activities at the ERC include premixed and partially premixed Spark-Ignition (SI) combustion, Conventional Diesel Combustion (CDC) and advanced Compression Ignition (CI)

engine studies. Much recent research at the ERC and elsewhere has focused on improving the understanding of ignition, which is highly dependent on the chemical composition of the fuel, and in increasing the quality of the air–fuel mixture for improved combustion efficiency in both SI and CI engines. Research progress has been aided by the advent of new developments in laser-based diagnostics that permit characterization of in-cylinder flows, combustion temperatures and species concentrations in unprecedented detail, together with the development of accurate Computational Fluid Dynamics (CFD) models. The latter has been facilitated by the more than 10,000-fold increase in computer speeds over the past 15 years.

Indeed, current multi-dimensional CFD tools have become sufficiently mature to guide the design and development of more efficient and cleaner IC engines [3]. Modeling is aiding the development of new Low Temperature Combustion (LTC) concepts that provide previously unimaginable efficiencies. LTC is also desired because low combustion temperatures result in NO_x reduction due to the high activation energy of NO formation reactions. LTC strategies include Homogeneous Charge Compression Ignition (HCCI), Premixed Charge Compression Ignition (PCCI) and Reactivity Controlled Compression Ignition (RCCI). These and other advanced combustion technologies are being pursued by all major engine companies, by the U.S. Department of Energy [4] and by Government laboratories.

2.1. Engine modeling

Instead of describing engine processes empirically, as in classical thermodynamically-based analyses, comprehensive computer codes are now heavily used in engine research. The governing Navier Stokes partial differential conservation equations are solved on a numerical mesh that follows the time-varying engine geometry during each engine cycle. Submodels are still required to describe processes that occur on time and length scales too small to be resolved in the simulations. But, these models have universality, since they refer to “micro-scale” processes that are common to general flows. For example, most wall boundary layers are too thin to be resolved on a practical engine CFD mesh, but adequate wall heat transfer predictions can be obtained with “law-of-the-wall-based” submodels that use local information about the mean flow in the computational cells at the combustion chamber walls. Sub-model development often relies on experiments conducted in more controlled environments than engines, such as in spray chambers, steady pipe flows or shock tubes. Direct Numerical Simulation (DNS) is too computer time intensive for practical engine simulation, but can provide insights about micro-scale processes, such as turbulence-chemistry interactions in flames.

2.2. Engine experiments

CFD model development benefits greatly from closely coordinated companion experiments. Engine experiments are difficult to perform in the hostile engine environment and they are complicated by phenomena such as cycle-by-cycle variability. However, they are critical to provide insights into processes that can lead to engine performance improvements. Diagnostics such as Planar Laser Induced Fluorescence or Incandescence (PLIF and LII), chemiluminescence (imaging and emission spectra) and soot thermal emission provide detailed information about in-cylinder spatial and temporal distributions of important species, including combustion intermediates, radicals and particulates. Details of the flow field can be obtained using Particle Image Velocimetry (PIV) or Phase Doppler Anemometry (PDA) techniques for spray drop size and velocity analysis. Of course, use of these techniques requires optical access to the combustion chamber, and this can necessitate

unavoidable compromises in engine geometry and/or operating conditions. However, the impact of such simplifications can also be assessed with CFD modeling.

High-resolution endoscopic imaging of combustion is less intrusive and also provides valuable information. For example, in SI engines the extent and causes of cyclic variability due to spark kernel growth and knock processes can be studied. In Gasoline Direct Injection (GDI) and diesel engines, details of the penetration and mixing of injected fuel sprays and their possible impingement on chamber walls can be visualized. The trend toward high-speed (>10 kHz frame rate) imaging diagnostics (enabled by commercially available high-speed cameras and high-repetition-rate lasers) allows key processes to be followed in time over hundreds of consecutive engine cycles. This is especially valuable for characterizing cyclic variation and rare stochastic events that limit engine performance.

Out-of-engine experiments also provide valuable information for understanding engine processes. For example, shock tube and rapid compression machine experiments provide needed data about the ignition characteristics of fuels. Constant volume combustion vessel experiments provide information about spray vaporization, fuel–air mixing, spray ignition, flame lift-off and fuel effects on particulate (soot) formation and oxidation. Flame speed measurements (both laminar and turbulent) are helpful for the development of flame propagation models. However, it is important that the experiments cover the regimes of temperature, equivalence ratio (Φ), turbulence, pressure and composition (including exhaust gas recirculation (EGR)) of interest in engines.

3. SI engines

Arguably, the SI engine features the most complex combustion process of all IC engines. The in-cylinder turbulent combustion is driven by complicated aero-thermo-chemical interactions that occur on vastly different time- and length-scales (i.e., scales ranging from the molecular to the device level). In fact, in spite of decades of research, the basic fact that SI engines can operate over a speed range from hundreds up to tens of thousands of revolutions per minute (rpm) can still not be explained satisfactorily. A simple Mallard–LeChatelier analysis shows that, for the flame speed to scale with rpm in a reaction–diffusion system (as required to explain the speed trend) both the diffusion and reaction terms must scale proportionally with rpm. However, the burning rate is known to be influenced by fuel effects, and mechanisms that explain the flame's dual sensitivity to turbulence and chemistry are largely unknown, with the result that SI engine modeling is still largely empirical.

In an SI engine the combustion duration, which is determined by the flame speed, is strongly dependent on turbulence. This is exploited in high performance (e.g., racing) engines by designing the combustion chamber to generate high turbulence. However, the consequence is that in-cylinder flow velocities are also increased, and this leads to a trade-off between fast combustion for improved work extraction and higher convective wall heat losses. The high heat losses also partly explain the relatively poor thermal efficiency of the SI engine.

Combustion models must account for the dynamic balance between large-scale mixing, small-scale or sub-grid-scale turbulence-chemistry interactions and chemical kinetics processes, as depicted schematically in Fig. 1. Popular models are classified as turbulent mixing-controlled, flamelet or PDF approaches. The simplest mixing-type model introduces a characteristic timescale to describe large scale mixing or diffusion (i.e., the resolved turbulent transport on the grid), together with a combination of mixing and kinetic (Arrhenius) species conversion rates for modeling sub-grid-

scale reaction. In this case, the sub-grid-scale turbulence-chemistry interactions within the resolved thickened flame or flame brush are modeled as a blended timescale between the two limits of large scale mixing and volumetric (chemical) heat release.

Flamelet models solve transformed reaction–diffusion equations based on a progress variable or non-reacting scalar, where the diffusion term is assumed to scale with the large-scale turbulence. PDF methods use assumed or computed weighting strategies to sample kinetic rates within the flame brush that lie between the burned and unburned gas temperatures. In our opinion the most practical modeling approach is the level set method (e.g., G-equation) which tracks the flame surface evolution. However, this model requires that the turbulent flame speed be specified, a priori. This is done using semi-empirical correlations that are functions of the local turbulent kinetic energy (i.e., rpm) and the mixture and thermodynamic conditions.

An important SI engine research area focuses on the initial spark kernel growth, since this has a major effect on the combustion timing. In addition to the details of the spark ionization and gas breakdown processes, kernel growth is strongly influenced by the turbulent flow conditions at the spark plug, which in turn, reflect complex flow behaviors that can vary from engine cycle to cycle. Some of these flow variations can be traced to flow features generated during the intake process, such as vortex shedding and flow separation from intake valves, and even to transient wave dynamics in the intake runners. The ignition process occurs below the scale of resolution of the numerical mesh in practical simulations, thus Lagrangian particles are often used to track the developing flame until it reaches the scale of resolution of the mesh, as depicted in Fig. 1.

An additional long standing SI engine research topic concerns engine knock and methods to mitigate it. Knocking combustion is an abnormal combustion phenomenon which produces loud noise and rapid cylinder pressure rise and can result in engine damage. For downsized and boosted SI engines, knock represents a stringent constraint since it prohibits the use of more advanced spark timings, higher compression ratios and/or higher boost pressures. The spark timing may need to be substantially retarded relative to the Maximum Brake Torque (MBT) timing to avoid pre-ignition, thus preventing maximum thermal efficiency from being achieved.

Downsize/boosting is a major development trend for SI engines, and therefore the ability to predict knock is becoming more-and-more critical. It is generally accepted that engine knock is caused by the volumetric auto-ignition of a portion of the end-gas ahead of the propagating flame (also depicted in Fig. 1). The extremely rapid heat release associated with end-gas auto-ignition causes sharp increases in local pressure and the propagation of large amplitude acoustic pressure waves across the combustion chamber. The temperature and pressure histories of the end-gas are, in turn, governed by the phasing and rate of development of the propagating turbulent flame, thus accurate modeling of end-gas auto-ignition must be coupled with accurate turbulent flame propagation models. Multidimensional modeling based on detailed chemical reaction kinetics is required for accurate knock prediction, since the assumption of simpler kinetics (e.g., single-step global chemistry) ignores important auto-ignition characteristics of hydrocarbon fuels, such as cylinder pressure effects and two stage ignition.

The unburned mixture in the end-gas is constantly compressed by the propagating turbulent flame, and it ignites under a local volumetric or HCCI-like condition in normal knock. However, in direct-injected, boosted, downsized engines operating at low speed and high load, a poorly understood phenomenon known as “super-knock” can occur. Here, one out of every few ten to a hundred thousand engine cycles suddenly exhibits a random large amplitude knocking event that can, in extreme cases, catastrophically

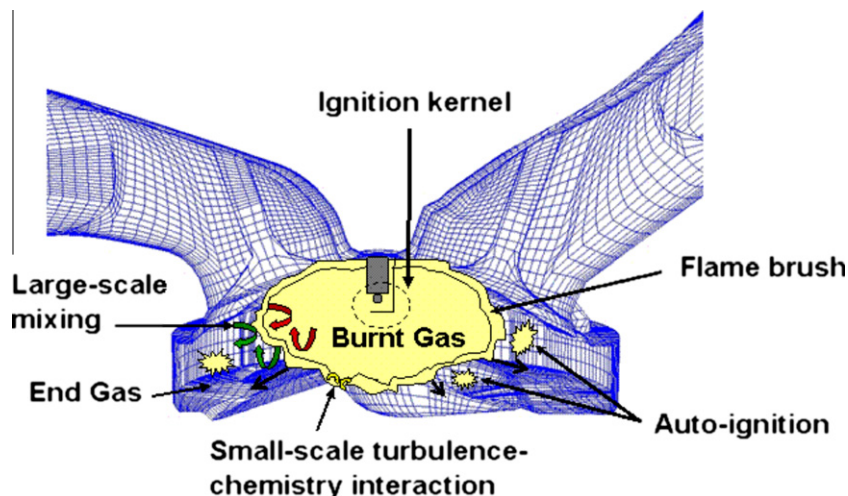


Fig. 1. Spark ignition engine processes.

destroy an engine. Superknock has variously been attributed to the transport and accumulation of oil droplets from the ring-pack or past the valves, which can serve as ignition sources, or to the build-up and break-off of combustion chamber deposits or other “hot spots”. Methods to eliminate superknock or Low Speed Pre-Ignition (LSPI) are under intense investigation. These include improved spray targeting and the use of mild EGR. The highly intermittent and random character of LSPI presents an especially severe challenge to both experimental diagnostics and predictive modeling.

In stoichiometric premixed charge SI engines, Unburned Hydrocarbons (UHC), CO and NO_x emissions are effectively controlled with the 3-way catalyst, which was a breakthrough technology developed in the 1960s and 1970s. Over 99% of regulated emissions have been removed from light-duty vehicle exhaust since 1970. Since these engines generally operate at very high burned gas temperatures and also avoid fuel rich equivalence ratios, soot emissions are also reduced. However, the 3-way catalyst is not effective for lean burn GDI engines when operated in a partially-premixed or stratified mode where NO_x reduction is not feasible due to the presence of oxygen in the exhaust gas. In addition, soot formation increases due the presence of locally rich regions (as in diesel engines), and methods for soot characterization and mitigation are the subjects of much current research also in gasoline-fueled SI engines. New and impending regulations mandate not only allowable exhaust soot mass, but also impose soot particle number density limits. Thus, models to predict particulates in SI engine combustion are urgently needed to aid engine development activities.

4. Diesel engines

Diesel engines are attractive because of their superior fuel efficiency and because of the global demand to reduce CO₂ emission from automotive engines, which is directly related to fuel consumption. The modern ‘clean’ automotive diesel engine is 20–40% more fuel efficient than its gasoline counterpart. The improved efficiency is partly due to the fact that load control is achieved without throttling the intake air flow as is required in the stoichiometric SI engine, and thus breathing or pumping losses are reduced. Instead, load control is achieved by varying the amount of fuel directly injected into the cylinder.

Much current research is thus aimed at improving the understanding of diesel sprays, such as the Sandia Engine Combustion

Network collaboration [5]. The ECN includes round-robin testing of standardized injectors and compares results from various experimental and modeling approaches and groups, internationally. New insights about diesel spray behavior are being obtained from these and other out-of-engine experiments. Novel techniques, such as phase-contrast X-ray radiography and ballistic imaging are providing insights about breakup mechanisms and nozzle cavitation and fuel effects.

Optical engine experiments allow spray penetration and targetting effects on UHC, CO, NO_x and soot emissions to be characterized, and provide data for CFD model validation. For example, diesel combustion simulations are compared with experimental OH PLIF measurements in Fig. 2 for three different diesel combustion

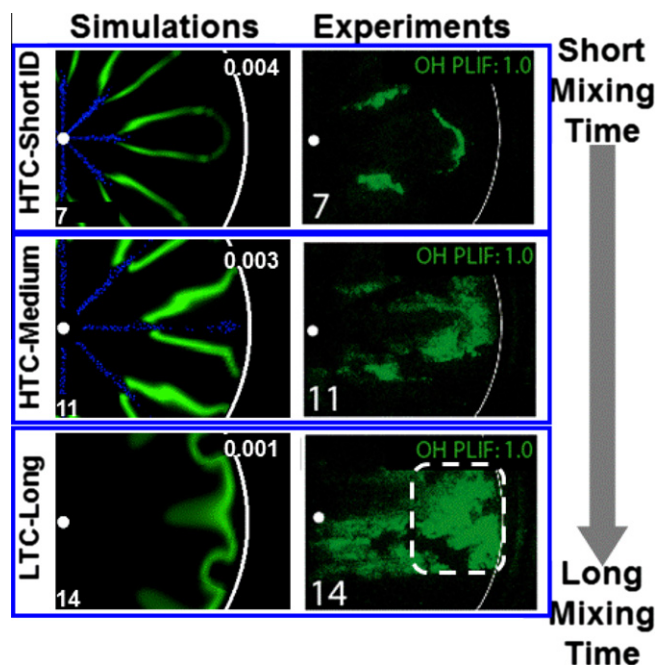


Fig. 2. Predicted (left) and measured (right) OH distributions in a plane through the sprays for operation in three different diesel combustion regimes. Top: HTC short ignition delay; Middle: HTC, medium ignition delay; bottom: LTC, long ignition delay. White dot at left of images shows location of injector nozzle; white arc at right is the cylinder liner. Numbers at bottom left indicate crank angle after start of injection, and relative camera gains at top right. White rectangular region in experimental LTC image indicates location of OH determined by comparing on and off-line PLIF data. The blue particles in simulations identify liquid jets.

scenarios (details of operating conditions are in [6]) (the presence of OH is an indicator of the main heat release event). The results show the dramatic dependence of diesel flame structure on the time available for fuel–air mixing before combustion is initiated. The High Temperature Combustion (HTC) short-ignition delay (ID) case is representative of Conventional Diesel Combustion (CDC). Here a 1–2 mm thick diffusion flame (as visualized by the OH contours) is anchored some distance downstream of the nozzle at the so-called flame lift-off location. In the medium-ignition delay case, the diffusion flame thickness increases to 4–6 mm and the lift-off length increases. In the Low Temperature Combustion (LTC) long-ignition delay case, the OH spreads throughout the jet, and the combustion represents a Premixed Charge Compression Ignition (PCCI) situation. As can be inferred, the reaction rate dependence on injection-generated mixing decreases with increasing ignition delay, and the reaction zone thickness increases with increased mixing time.

The model flame structures in Fig. 2 were predicted without considering sub-grid scale turbulence–chemistry interactions. Ignition occurs in a premixed region and combustion is controlled by diffusion and large scale (i.e., resolved scale) mixing processes. Indeed, simulations made using the level set G-Equation model gave virtually identical results, except in the immediate vicinity of the flame anchor point [6]. (Note that the flame propagation velocity is zero in a diffusion flame, except near the lift-off point. This is captured in the G-Equation model since the flame speed is a function of the laminar flame speed, which depends on the local equivalence ratio.)

Conventional diesel combustion is characterized by high NO_x and soot emissions, since the combustions spray spans a wide range of local equivalence ratios and temperatures. Measures introduced

to meet emissions mandates, such as the use of non-optimal fuel injection timings (to allow more time for fuel–air mixing), the use of large amounts of EGR (to dilute the charge and lower local temperatures), or the use of ultra-high injection pressures (to promote vigorous mixing – injection systems with 3000 bar injection pressure are now commercially available) tend to reduce diesel engine fuel efficiencies, and also increase engine expense.

Most diesel engine manufacturers have elected to use Selective Catalytic Reduction (SCR) exhaust gas after-treatment for NO_x reduction. However, with SCR there is also a fuel penalty since a reducing agent, such as urea (carbamide) is sprayed into the exhaust stream at rates (and cost) of about 1% of the fuel flow rate for every 1 g/kW h of NO_x reduction desired. Depending on the engine calibration, this can amount to a 2–4% fuel penalty. Soot control is achieved using Diesel Particulate Filters (DPF), which require periodic regeneration by adjusting the fuel–air mixture strength to increase exhaust temperatures to burn off accumulated soot. This imposes as much as a 3% additional fuel penalty. It is worth noting that the cost of the after-treatment system on a modern truck is roughly the same as the cost of the engine itself, and is thus a major expense to the consumer. However, the effectiveness of modern diesel exhaust gas after-treatment systems is remarkable [7].

In conventional diesel engines fuel is injected near Top Dead Center (TDC). As seen in Fig. 2, ignition and combustion occur while the fuel is being injected, and the combustion rate is controlled by the injection and air entrainment rates into the spray jets. The mixture equivalence ratio varies within the combustions spray and regions of high temperature and relatively low Φ lead to NO_x formation, while soot formation is favored in high Φ , intermediate temperature regions. These trends are also seen in Fig. 3, which summarizes engine-out CO, HC, NO_x and soot

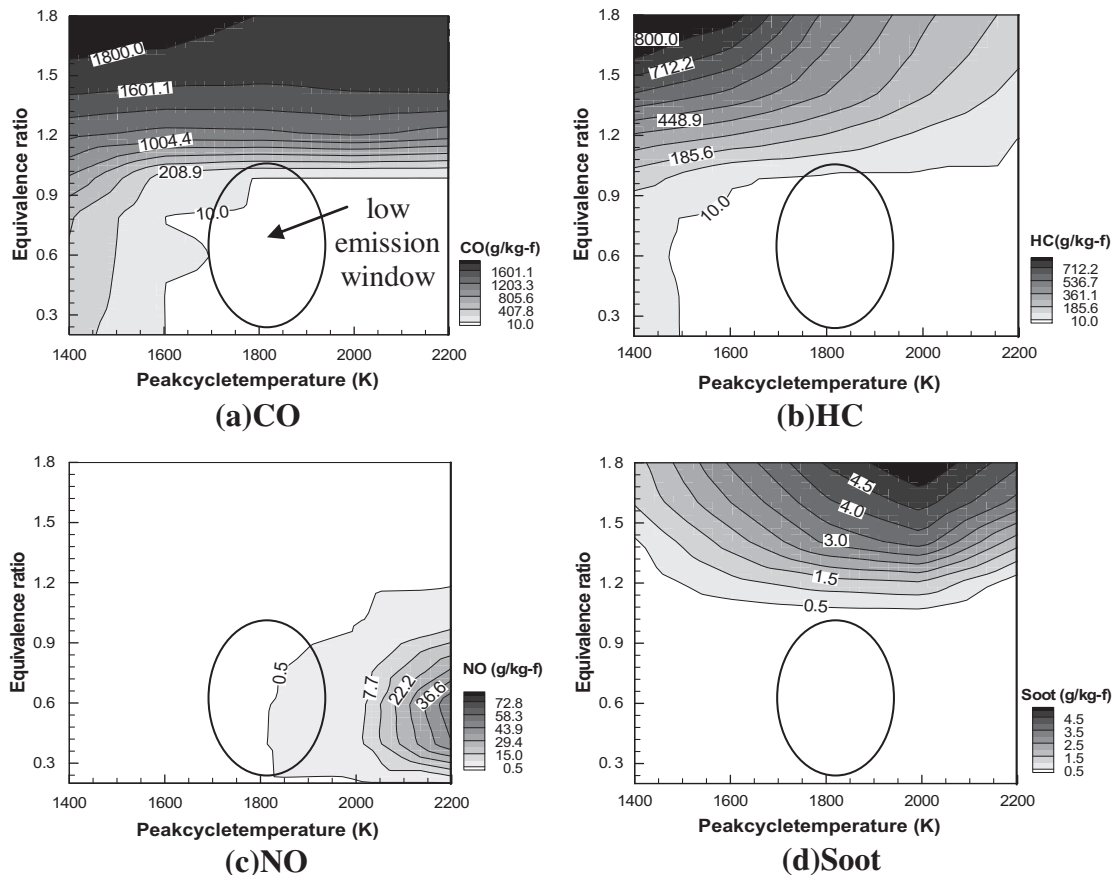


Fig. 3. Predicted HCCI engine-out (a) CO, (b) HC, (c) NO, and (d) soot emissions on equivalence ratio–peak cylinder temperature maps ($m_{\text{fuel}} = 20$ mg, $S = 2000$ rev/min, IVC = -142° ATDC) [11]. Ovals indicate location of low emissions window region.

emission predictions from HCCI engine simulations as a function of Φ and the corresponding peak cycle gas temperature. Although this analysis does not consider mixing effects, the Φ – T plot [8] has been found to be very useful for understanding engine combustion and emissions, and it helps identify the conditions necessary for low emissions operation.

For example, the use of multiple, appropriately timed injections can reduce the extent of overly fuel rich regions in the combustion chamber, and thus reduce soot formation. “Lifted flame” combustion is a means to reduce both NO_x and soot, in-cylinder. Increasing the ignition delay anchors the diesel flame sufficiently far downstream of the injector nozzle that the air entrained into the jet yields local equivalence ratios below about 2 at the lift-off point (c.f., HTC Medium ID case, Fig. 2). $\Phi < 2$ has been found to be sufficiently lean for “smokeless” combustion. Extended ignition delays can be achieved by using a lower Cetane Number (CN) fuel, together with appropriate injection and thermodynamic conditions. The use of oxygenated fuels also reduces the amount of entrained air needed to reduce the local equivalence ratio, and thus reduces soot emissions. However, oxygenated fuels can also increase NO_x emissions by moving the combustion closer to stoichiometric operation, resulting in higher flame temperatures.

5. Advanced low temperature combustion engines

HCCI is a promising combustion strategy because the dilute homogeneous charge avoids locally high temperatures or equivalence ratios in the chamber. As seen in Fig. 3, this allows operation in a low emissions window. Increased thermal efficiency is also seen with low temperature combustion strategies because of lower wall heat transfer losses. LTC engines operate fuel lean, which yields higher specific heat ratios and hence increased work extraction. However, LTC operation reduces the available exhaust energy, which is needed for turbocharger operation, and also increases combustion irreversibility, due to the need to transfer heat to more inert gas. However, the net effect is positive – for example, HCCI is a high efficiency, low emissions combustion strategy.

Unfortunately, despite the advantages of HCCI, several problems limit its adoption. The first difficulty is the achievement of a homogeneous charge in the engine. Many methods of fuel preparation have been proposed, such as port injection or early direct injection with a narrow injected included spray angle to avoid spray-wall impingement. This latter approach is referred to as Partially Premixed CI, since with late injections the charge may still be somewhat inhomogeneous at ignition. A second difficulty is HCCI’s limited operating range. Due to the nature of volumetric combustion, the cylinder contents ignite virtually simultaneously and this can produce unacceptable noise and knocking at high loads. Attempts have been made to increase load by injecting water, applying high EGR rates, or by introducing temperature stratification in the cylinder.

An additional difficulty with HCCI is control of the start of combustion timing. In conventional CI engines, start of combustion is controlled by the fuel injection timing, while in SI engines the spark initiates combustion. On the other hand, HCCI ignition is controlled by the charge mixture temperature, composition and compression history. More control is possible with a low reactivity fuel, such as gasoline whose high resistance to auto-ignition allows more mixing time prior to combustion, producing lower local Φ and thus lower NO_x and soot emissions. Indeed, the best fuel for HCCI operation would have auto-ignition qualities between those of diesel and gasoline. High load operation is favored with a low CN (e.g., high octane number gasoline), while low load operation favors a high CN (e.g., diesel).

A practical strategy might use dual mode combustion, with HCCI at low and medium loads and conventional combustion at

high loads. Extended operating range has been demonstrated using spark-assisted HCCI combined with multiple injection/multiple ignition and valve-timing strategies. In Gasoline Direct Injection Compression Ignition (GDICI) operation, more control over the start-of-combustion timing can be achieved with suitably timed multiple injections to create partially-premixed (or “premixed enough”) in-cylinder Φ stratification. Since higher Φ regions are more reactive, this leads to sequential auto-ignition at different spatial locations in the chamber and pressure rise rates are reduced, with the result that higher loads can be achieved.

Greatly improved combustion control has been demonstrated at the ERC with dual fuel CI combustion. In-cylinder fuel blending is arranged using port fuel injection of a lower reactivity fuel (e.g., gasoline), coupled with optimized in-cylinder multiple injections of more reactive fuel (e.g., diesel). The resulting strategy has been called Reactivity Controlled Compression Ignition (RCCI) and it generates both equivalence ratio and reactivity stratifications in the chamber. Combustion progresses sequentially from the high reactivity regions to low reactivity regions, thereby effectively lowering pressure rise rates. RCCI does not require high fuel injection pressures since the injections occur well before TDC, thus providing time for fuel vaporization and mixing. Indeed, excellent results have been achieved with the diesel injector replaced by a low pressure GDI injector. RCCI extends the engine’s operable load range beyond that of HCCI or PCCI since fuel blending allows the combustion to be tailored. Indeed, gasoline-diesel RCCI has been demonstrated up to 23 bar gIMEP in a heavy-duty diesel engine with a compression ratio of about 12:1.

CFD modeling was a key enabling technology in the development of RCCI. CFD, combined with genetic algorithm optimization techniques, discovered fuel injection strategies and safe operating conditions with acceptable pressure rise rates [9]. U.S. EPA 2010 heavy-duty diesel engine NO_x and soot emission mandates were met in-cylinder, without the need for after-treatment, while achieving gross indicated thermal efficiencies in excess of 56%. This efficiency is about 10% higher than conventional diesel combustion (i.e., about 20% less fuel consumed). Further experiments in the ERC’s single-cylinder heavy-duty diesel engine with 18.7:1 compression ratio have demonstrated gross indicated thermal efficiencies reaching 60% [10], and pathways to even higher efficiencies have been identified. These efficiencies rival those of any other powerplant, including those of state-of-the-art, MW-level natural gas combined-cycle electrical power stations. The high efficiency of the ERC’s engine was achieved using E85 as the low reactivity fuel (i.e., high ON) and gasoline doped with a cetane improver (ethyl-hexyl-nitrate) as the high reactivity fuel (i.e., high CN) to increase the extent of in-cylinder fuel reactivity gradients. In addition, a low-surface-area piston was used to further reduce wall heat losses, which are already low due to the low chamber gas temperatures.

In contrast to other LTC concepts, the combustion phasing of RCCI can be altered by adjusting the proportions of the more and less reactive fuels on a same- or next-cycle basis with appropriate combustion feedback control. RCCI also offers considerable fuel flexibility. High-efficiency, low-emissions operation has been demonstrated using direct-injected diesel with port-injected methanol and natural gas, and even with hydrated ethanol, which cannot be used in either SI or CDC engines due to its poor reactivity. Hydrated ethanol is significantly cheaper to produce, since removing all the water from ethanol is extremely costly. In addition, port injection of gasoline, plus a small quantity of cetane improver added to the direct injected fuel (also gasoline), allows an RCCI engine to operate on a single fuel (i.e., gasoline), together with a windshield-wiper bottle sized supply of cetane improver, which is topped-up every oil change interval.

A remaining challenge with LTC concepts is UHC and CO emissions, which increase unless combustion temperatures exceed about 1600 K under lean conditions (see Fig. 3). However, recent RCCI experiments show that the use of a Diesel Oxidation Catalyst (similar to the SI engine's 3-way catalyst) can be effective for exhaust gas UHC/CO reduction. The use of the DOC also decreases the already extremely low amount of engine-out Particulate Matter (PM), which is primarily comprised of organic carbon (i.e., condensed heavy HCs). Little is known about the formation mechanisms of this type of PM. Also, further research on low temperature oxidation catalysts would be very helpful.

6. Closure

This article has attempted to identify research areas that, in this author's opinion, will help address the urgent fuel usage and pollutant emission problems associated with transportation and other internal combustion engine applications. Three classes of IC engines were discussed and contrasted – Spark-Ignited, Conventional Diesel and Low Temperature Combustion, and their operating regimes are summarized conceptually in Fig. 4. It is noted that the ubiquitous gasoline SI engine, which relies on high temperature turbulent flame propagation, is controlled by complex physical and chemical kinetic processes, including both large- and small-scale mixing (indicated in Fig. 4 by bent arrows in the flame brush). The SI engine is also the least fuel efficient, partly because its high flame temperatures lead to high wall heat transfer losses. High flame temperatures also lead to high NOx emissions, but tail-pipe emissions are low, thanks to the low cost 3-way catalyst. However, a remaining concern is emissions of N₂O and other UHC pollutants during cold-start (i.e., before catalyst “light-off”). N₂O has a long atmospheric lifetime (approximately 120 years) and is about 300 times more effective than CO₂ as a GHG. In stratified charge GDI engines, the combustion spans a region between the rich and lean limits (also depicted in Fig. 4), and this necessitates advanced and costly after-treatment measures for both NOx and soot control.

The conventional diesel engine is 20–40% more fuel efficient than the SI engine. The combustion process is also less complex, since it does not rely on flame propagation. Instead, a diffusion flame is formed and the rich and lean flammability limits determine the thickness of the flame surrounding the fuel spray (depicted by the broad horizontal region around stoichiometry in Fig. 4). Combustion is controlled by large-scale fuel–air mixing (de-

picted by large arrows in Fig. 4) and, unless high EGR levels are used, it features high local temperatures, leading to high NOx. Also, because the charge is stratified, fuel rich regions can lead to high soot. Meeting the simultaneous constraints of high-efficiency and clean combustion, in-cylinder, has been extremely challenging. This has necessitated the development of costly exhaust gas after-treatment systems.

The most fuel efficient and clean engines exploit compression ignition after the fuel–air mixing process is more-or-less complete, and the role of turbulent mixing is of secondary importance compared to chemical kinetics. Low temperature combustion regimes include the Premixed Charge, Reactivity Controlled and Homogeneous Charge Compression conditions depicted in Fig. 4. LTC operation is largely controlled by the details of the fuel's ignition chemistry. Indeed, the best fuel efficiency is achieved when the in-cylinder flow field is quiescent (i.e., turbulence and organized charge motion are small) to further reduce convective wall heat transfer losses. Thus, when trying to tame fluid mechanics and combustion in an IC engine, the lesson is “the simpler the better!”.

Advanced combustion strategies such as Gasoline-Direct-Injection (GDI) and Reactivity-Controlled Compression Ignition (RCCI) have demonstrated up to 20% improved fuel efficiency over standard diesel, and 40–50% over conventional SI gasoline engines. These technologies also offer significant cost advantages because expensive NOx and soot after-treatment and costly ultra-high injection pressure systems are not required. Although the combustion process may be “simpler” in advanced engines, advanced feedback control and high-performance air-handling systems will be required for optimal performance. However, the implications of the promising improvements in fuel efficiency of LTC engines are very significant. It has been estimated that if RCCI was adopted to replace the relatively inefficient SI engine, U.S. transportation oil usage would be reduced by 34%, which is 100% of current U.S. oil imports from the Persian Gulf. Even greater reductions in oil usage are possible if the efficiency improvements are combined with electric hybrid technologies in the vehicle.

Finally, the dual fuel RCCI engine has the further advantage of fuel flexibility. As long as the two fuels have significantly different reactivities they can be blended appropriately, in-cylinder, for optimal performance as a function of speed and load. RCCI can operate with a wide range of fuels, including gasoline, natural gas and diesel. It can also be used with a single fuel where one stream is added with a small amount of cetane improver, which is replenished at oil change intervals. In addition, RCCI can be used with alternative or renewable fuels, such as hydrated ethanol, methanol, and biodiesel. It is fair to say that the IC engine is a remarkably efficient device, and when matched with technologies that allow fuel flexibility, it provides a path away from the monopoly of fossil oil for our future energy security.

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References

- [1] Energy Technology Perspectives, International Energy Agency, Paris, 2012. Available from <<http://www.iea.org/publications/freepublications/publication/name,31269,en.html>>.

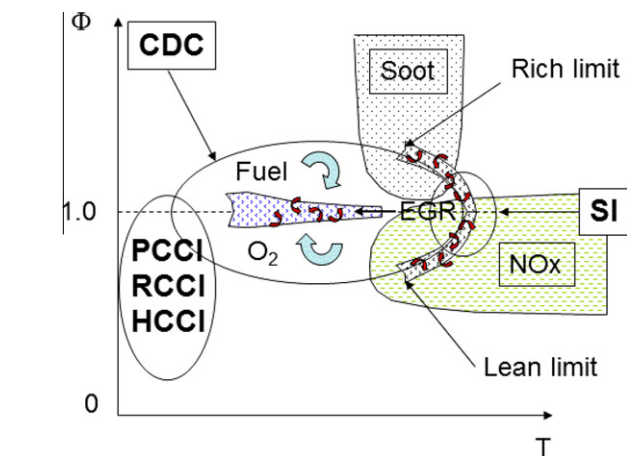


Fig. 4. Conceptual diagram of Conventional Diesel (CDC), stoichiometric and stratified Spark Ignition (SI), and Low Temperature Compression Ignition (P-R-HCCI) regime locations on the Φ - T map. The rich and lean limits determine the turbulent flame propagation limits of stratified SI operation. Use of EGR lowers peak temperatures.

- [2] Assessment of Fuel Economy Technologies for Light-Duty Vehicles, National Research Council, 2011, ISBN 978-0-309-15607-3.
- [3] Y. Shi, H.-W. Ge, R.D. Reitz, Computational Optimization of Internal Combustion Engines, 2011. Available from <<http://www.springer.com/engineering/mechanical+eng/book/978-0-85729-618-4>>.
- [4] DOE Vehicle Technologies Multi-Year Program Plan 2011–2015. Available from <http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/vt_mypp_2011-2015.pdf>.
- [5] <http://www.sandia.gov/ecn/workshop/ECN1.php>.
- [6] S.L. Kokjohn, R.D. Reitz, ASME, J. Eng. Gas Turbines Power 133 (2011) 102805–1–10.
- [7] Today's 18-wheeler diesel-engine truck would have to drive 143 miles on the freeway to put out the same mass of particulates as a single charbroiled hamburger patty! University of California Riverside Center for Environmental Research and Technology. Available from <<http://ucrtoday.ucr.edu/8896>>.
- [8] T. Kamimoto, M. Bae, High Combustion Temperature for the Reduction of Particulate in Diesel Engines, SAE paper 880423, 1988.
- [9] S.L. Kokjohn, R.M. Hanson, D.A. Splitter, R.D. Reitz, Int. J. Eng. Res. Special Issue on Fuel Efficiency 12 (2011) 209–226, <http://jer.sagepub.com/content/12/3/209.full.pdf+html>.
- [10] Splitter, D.A., High Efficiency RCCI Combustion, Ph.D. Thesis, University of Wisconsin-Madison, 2012.
- [11] S.W. Park, R.D. Reitz, Combust. Sci. Technol. 179 (11) (2007) 2279–2307.

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